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MONITORING THE PREY-FIELD OF MARINE PREDATORS: COMBINING DIGITAL IMAGING WITH DATALOGGING TAGS

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ABSTRACT

There is increasing interest in the diving behavior of marine mammals. However, identifying foraging among recorded dives often requires several assumptions. The simultaneous acquisition of images of the prey encountered, together with records of diving behavior will allow researchers to more fully investigate the nature of subsurface behavior. We tested a novel digital camera linked to a time-depth recorder on Antarctic fur seals (*Arctocephalus gazella*). During the austral summer 2000–2001, this system was deployed on six lactating female fur seals at Bird Island, South Georgia, each for a single foraging trip. The camera was triggered at depths greater than 10 m. Five deployments recorded still images (640 × 480 pixels) at 3-sec intervals (total 8,288 images), the other recorded movie images at 0.2-sec intervals (total 7,598 frames). Memory limitation (64 MB) restricted sampling to approximately 1.5 d of 5–7 d foraging trips. An average of 8.5% of still pictures (2.4%–11.6%) showed krill (*Euphausia superba*) distinctly, while at least half the images in each deployment were empty, the remainder containing blurred

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or indistinct prey. In one deployment krill images were recorded within 2.5 h (16 km, assuming 1.8 m/sec travel speed) of leaving the beach. Five of the six deployments also showed other fur seals foraging in conjunction with the study animal. This system is likely to generate exciting new avenues for interpretation of diving behavior.

Key words: Antarctic fur seal, *Arctocephalus gazella*, digital imaging, diving behavior, foraging, time-depth recorder.

Studies of the diving behavior of marine mammals are limited by our inability to comprehensively assess an animal's behavior beneath the water. Instrumentation deployed on marine mammals has become increasingly sophisticated since the first deployments of analog time-depth recorders (TDRs) in the 1970s (Kooyman *et al.* 1976, Le Boeuf *et al.* 1986). Recent technological advancements have incorporated a wide range of transducers which, in addition to depth, have provided information about variables such as swimming speed, light level, temperature, heart rate, and external sound (Ponganis *et al.* 1992, Butler 1993, Crocker *et al.* 1994, Fletcher *et al.* 1996, Boyd *et al.* 1999, Georges *et al.* 2000, Baird *et al.* 2001, Campagna *et al.* 2001). However, despite this, we cannot provide a complete view of the behavior and environment of marine mammals when they are submerged. This reduces our ability to put behavior into context, and is exemplified by the difficulties associated with determining the function of subsurface behavior and different types of dives (Schreer and Testa 1995, Hooker and Baird 2001). Attachment of a camera to the study animal allows the researcher to provide this context and, thus, to better assess the function of subsurface behaviors.

Our experience with recording diving behavior of Antarctic fur seals (*Arctocephalus gazella*) highlights the significance of this gap in our knowledge. Although we have a large sample of dive records from these animals (Croxall *et al.* 1985; Boyd and Croxall 1992; Boyd *et al.* 1994; Boyd 1996, 1999), we still have only a limited understanding of their fine-scale foraging behavior. For example, the formulation of energy-gain functions rests on the simple and potentially invalid assumption that time spent at depth is a reasonable proxy of foraging success (Boyd 1999).

The attachment of cameras to marine mammals is not a new concept. National Geographic Television "CRITTERCAM" deployments (a fusiform unit, 35 cm long, 10 cm in diameter, and weighing 2 kg in air) have been carried out on several pinniped, cetacean, and turtle species (Marshall 1998, Parrish *et al.* 2000, Heithaus *et al.* 2001). Other researchers have also designed units for specific projects (*e.g.*, a 35-cm long, 13-cm diameter unit, Davis *et al.* 1999). However, the specialized nature, large size, and high cost of these camera systems have often restricted their use to large-sized animals.

In the present study we describe a recently developed, smaller camera system, which is commercially available. The Underwater Timed Picture Recorder (UTPR; WildInsight Ltd., Ely, Cambridgeshire, UK[2]) uses a digital

[2] Use of trade names for commercial products does not imply endorsement by the authors.

camera interfaced with a time-depth recorder such that the camera is activated according to preset depth criteria. The use of a digital rather than analog system allows a reduction in overall size of the unit, and the system employs a range of preset sampling routines that will allow researchers to select sampling protocols according to their needs. The aim of our study was to test and demonstrate the capabilities of this system for deployment on a small pinniped, the Antarctic fur seal.

Methods

The UTPR had dimensions of 10.5 × 8.5 × 5.5 cm (Fig. 1) and weighed approximately 700 g in air and 200 g in water (commercial value approximately £4,500). The unit was composed of a digital camera (using components from a Sharp VN-EZ1H), a Mk7 time-depth recorder (TDR, Wildlife Computers, Redmond, WA, USA), a light source (31 LEDs providing 620 mW at 735 nm ± 25 nm), two rechargeable lithium batteries (1.35 AH Li+), and control circuitry to operate the system. The whole unit was solid-potted in epoxy to withstand pressure at depth (tested to 750 m). Data were recorded to a 64 MB SmartMedia card (larger data capacity versions of this card have become available since test deployments). The quantity of data that could be recorded was governed either by the memory space (for high resolution, or for images taken at high repetition rate) or by the battery power (for images taken at low repetition rate).

The link between TDR and camera allowed the user to preset the depth range (minimum and maximum depths) at which the camera was triggered. Each picture file was time stamped so that it could be linked with the information from the TDR. Since the TDR and camera clocks were independent, the system was set up to take a "clapperboard" picture prior to deployment to record the offset between clocks. Upon triggering, the camera took approximately 43 sec to warm up. This warm-up could be bypassed by maintaining the unit in "standby" mode, although with concurrent increased battery drain. In order to optimize the recording setup for the species on which the UTPR was deployed, a recording protocol was programmed into the camera during manufacture. Antarctic fur seals tend to dive in well-defined bouts in which individual dives last approximately two minutes within bouts of approximately 30 mins (Boyd and Croxall 1992). Because our primary interest was in obtaining pictures during the deepest portion of dives, we established a recording protocol to maximize the number of pictures from complete dives and to avoid the 43-sec initial warm-up period (Fig. 2).

Several recording modes were available: the camera could take still images (Joint Photographic Experts Group format—JPEG files), or movie images (Advanced Streaming Format—ASF files) at preset resolutions and recording frequencies (Table 1). Both resolution and compression had an effect on the resulting image quality. These are traded off against file size and, thus, also determined the number of images that could be stored. Decreasing resolution resulted in fewer pixels and a poorer quality image. Increasing the compression

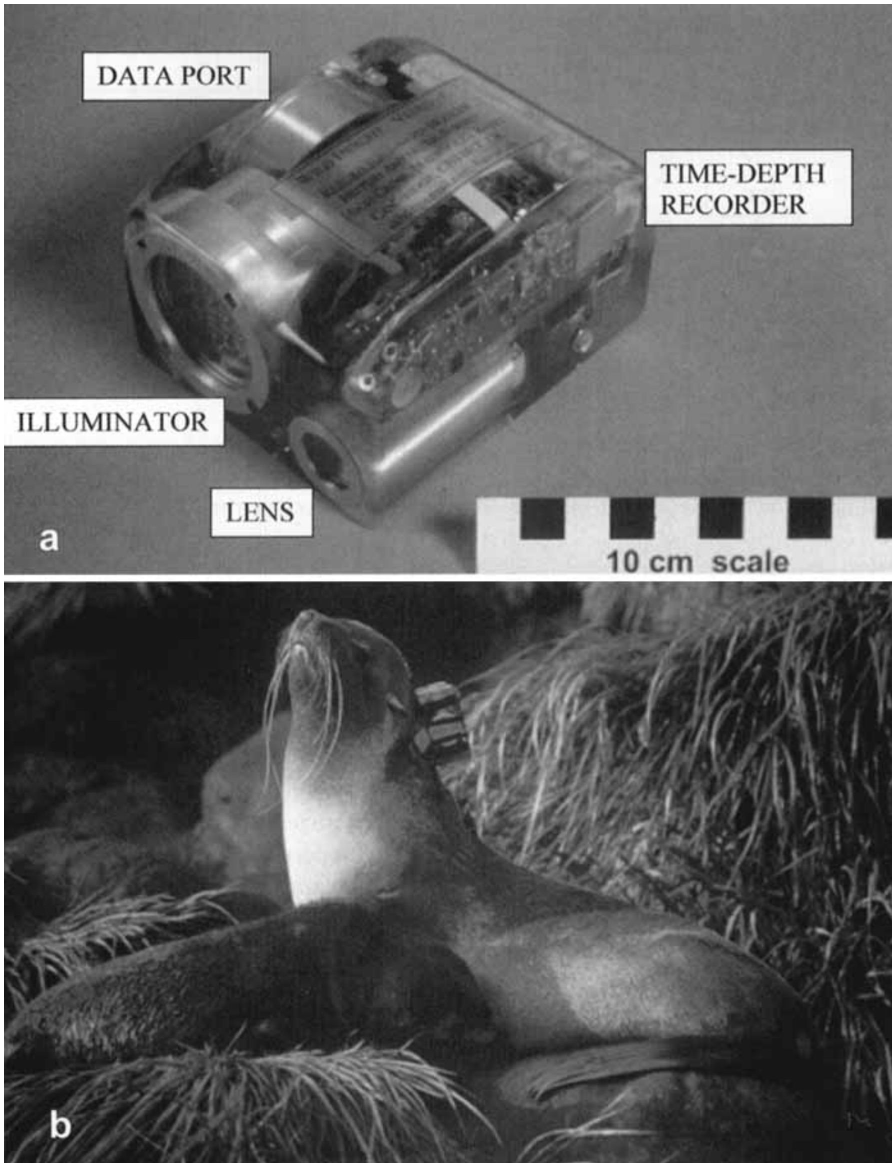

Figure 1. (a) Photograph of Underwater Timed Picture Recorder (UTPR), (b) UTPR deployed on a lactating Antarctic fur seal. UTPR is mounted on webbing and glued to the fur.

resulted in smaller files, as less information was transmitted and, so, also came at the expense of loss of quality. Additionally, a time-lapse mode potentially allowed the user to slow the movie recording settings by factors of 10, 40, or 100. The combination of recording frequency and the behavior of the study animal (proportion of time spent below 10 m), therefore, determined the total

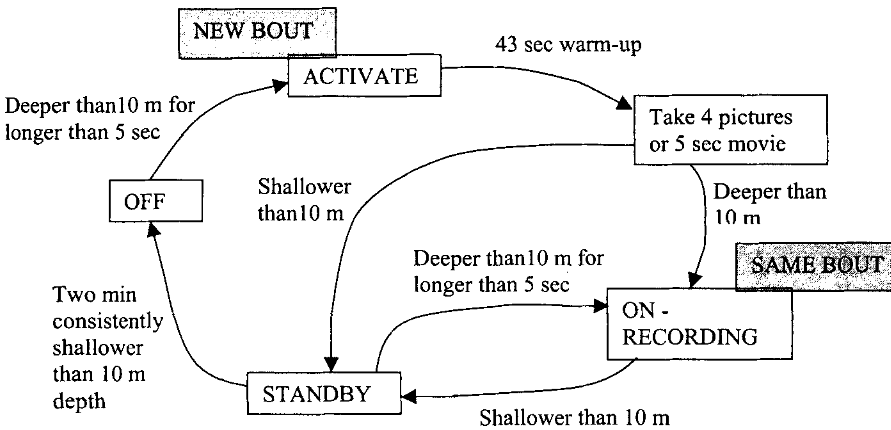

Figure 2. Protocol used to maximize recording time for deployment on fur seals. For illustration threshold depth is set at 10 m (although this can be modified prior to each deployment). Recording may be delayed by duty-cycling the TDR.

sampling duration over which pictures were taken. By default, the camera began sampling as soon as the depth criteria were first reached; however, the duty-cycling feature of the TDR could allow the user to delay the start of sampling.

The camera illuminator triggered each time the shutter opened. The shutter speed of the camera varied automatically depending on light level (ranging between ¼ and 1/4,000 sec for still images). However the illuminator provided output in 1/125-sec pulses, which were synchronized with the picture (still or movie) such that, although the shutter may open for longer, the effective shutter time for the picture will equal the duration of illumination. An automatic gain control set the light level of the picture in order to maximize contrast within the central portion of the image. The lens used was an adapted microscope objective with an extra field lens (view angle 30° horizontal, 24° vertical). The camera focus could be fixed at any distance from 15 to 150 cm, and we chose a preset focus of 30 cm.

Calibration

To calibrate the focal range and illumination range of the camera, we attached the system to a fixed measured meter length with intervals delineated by marked white nails at 10-cm intervals (Fig. 3). Test images were taken in low levels of downwelling illumination both facing toward and away from the surface in a range of depths from 0 to 30 m.

Field Deployment

We deployed the UTPR on lactating female Antarctic fur seals at Bird Island, South Georgia, (54°S, 38°W) during the austral summer of 2000–

Table 1. Preset recording modes. The effective surveillance window is shown for animals which spend approximately 10% of time beneath 10 m depth.

Mode	Camera setting	Compression	Resolution	Frame rate	Recording time*	Effective surveillance window
Still	FINE	Low	640 × 480	1 frame per 3 sec	30 min	5 h
	NORM	High	640 × 480	1 frame per 3 sec	1 h	10 h
Movie	¼ VGA	Low	320 × 240	5 frames per sec	20 min	3 h 20 min
	S-FINE	Low	160 × 120	15 frames per sec	20 min	3 h 20 min
	FINE	Medium	160 × 120	12 frames per sec	40 min	6 h 60 min
	NORM	High	160 × 120	10 frames per sec	2 h	20 h
	LP	Very high	160 × 120	2 frames per sec	4 h	40 h
Time lapse (10×)	¼ VGA	Low	320 × 240	1 frame per 2 sec	3 h 20 min	33 h 20 min
	S-FINE	Low	160 × 120	1 frame per sec	3 h 20 min	33 h 20 min
	FINE	Medium	160 × 120	1 frame per sec	6 h	60 h

* Recording times are given for 64 MB SmartMedia card and vary to some extent depending on image composition (*i.e.*, blank images have smaller file size).

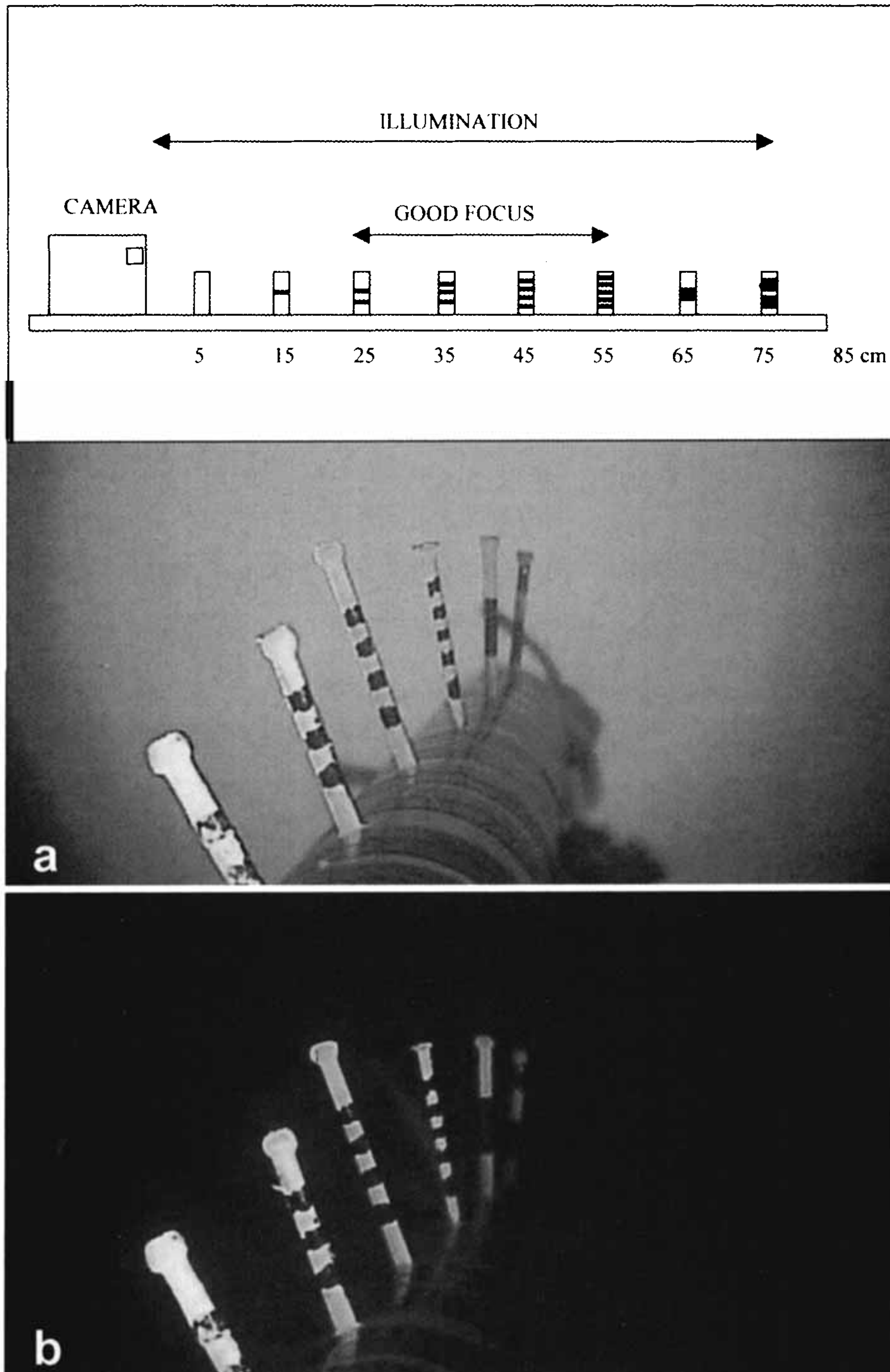

Figure 3. Test deployment showing depth of view of UTPR in two light conditions (a) with camera facing the water surface (b) with camera facing down.

2001. Female seals were selected based on large size and the presence of a healthy (*i.e.*, large) pup. Seals were captured and held using standard methods. Each seal was weighed (± 0.5 kg, 100-kg Salter spring scale), measured for length and pectoral girth (± 0.5 cm), and a numbered white plastic cattle ear rototag (Jumbo Tags, Dalton, Henley-on-Thames, UK) was placed in the trailing edge of each foreflipper. To ensure that our attachment system was robust, we tested the system using a dummy unit of identical size, shape, and weight to the camera. Thereafter we continued deployments of a single camera unit each for a single foraging trip. The TDR was programmed to record depth at 1- or 2-sec intervals. The UTPR was attached using cable ties to nylon webbing which was glued (quick-setting epoxy) to the fur of the seal (Fig. 1). A 40-g, 165-MHz radio-transmitter (Sirtrack Ltd., Havelock North, New Zealand) was also fitted to the fur directly behind the camera to enable relocation when the animal returned to shore. Radio signals were monitored with an automated scanning receiver located less than 100 m from the point at which fur seals were captured. Radiosignals were received only when the transmitters' antennas were exposed to air, which allowed monitoring of the presence or absence of these seals on the beach. The camera was recovered after a single foraging trip by recapturing the animal and cutting the cable ties, leaving the webbing attached to the animal's fur until it was molted at the end of the summer season.

Results

Calibration

Calibration tests of the camera were conducted at the south end of Bird Sound (an area through which Antarctic fur seals swim en route to their foraging sites) at 2300–2340 GMT, 12 December 2000. Even with relatively low levels of surface light, an appreciable amount of downwelling light reached the camera when oriented toward the water surface (Fig. 3). The system of marked nails showed that items between 25 and 55 cm from the camera lens were well focused, and that the illumination of white objects reached up to 75 cm from the lens (at least within the typical conditions found in the local environment).

Field Deployments

The camera was successfully deployed and data were recovered from six female Antarctic fur seals (Table 2, Fig. 1). The attachment system used was adequate for deployments of up to 10 d; upon recovery there was no sign of wear or loss in the cable tie, webbing, or epoxy used to bind the unit to the fur. For initial deployments we positioned the camera approximately between the shoulder blades of the animal, but following initial successful trials, we moved the position of the unit toward the animal's neck. This resulted in fewer frames with the animal's head obscuring the view (Table 3).

Table 2. Details of deployments carried out and data collected. Trip duration was calculated from radio-tag presence as recorded by automated receiver.

Seal ID	Weight (kg)	Length (cm)	Girth (cm)	Deployment dates	Trip duration (days)	Mode	Footage (# stills/ movies)	Data size (MB)	Recording time
w6160	49	131	91	07–11 Dec	4.73	Still, norm	2,213	27.7	1625–0328, 07–08 Dec
w2955	40	130	84	16–23 Dec	6.71	Still, norm	3,293	39.1	2047–0114, 16–18 Dec
w6710	38.5	122	89	27 Dec–01 Jan	5.02	Still, fine	911	54.3	1306–1948, 27 Dec
w6714	40	132	89	03–09 Jan	6.61	Movie, ¼ VGA	18	61.7	0329–1650, 03 Jan
w3895	47	132	92	10–15 Jan	3.50	—	—	—	—
w6726	41.5	130	92	06–13 Feb	6.86	Still, fine	930	55.1	1155–2239, 06 Feb
w6728	42.5	132	88	17–26 Feb	8.31	Still, fine	941	55.0	0428–1233, 17 Feb

Table 3. Still images collected from deployment on Antarctic fur seals. Bout and dive criteria are those shown in Figure 2 (*i.e.*, dives are excursions deeper than 10 m for over 5 sec, and bouts are separated by 2 min consistently shallower than 10 m).

				# images containing				
Seal ID	# bouts	# dives	# images	Clear krill	Indistinct krill	Other seals	Bubbles	Focal seal's head
w6160	27	80	2,213	53	113	0	0	335
w2955	25	134	3,293	297	378	8	4	466
w6710	7	38	911	106	83	3	3	247
w6726	37	109	930	83	97	11	15	6
w6728	13	85	941	101	164	33	16	6

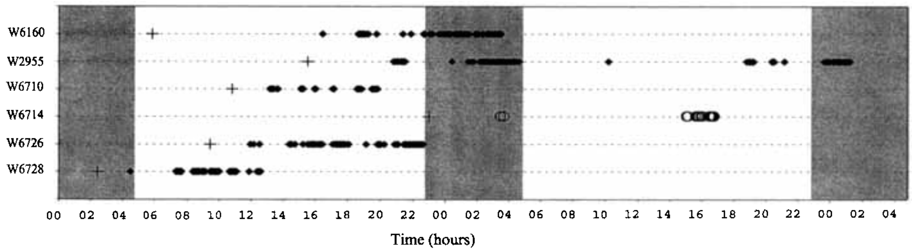

Figure 4. Recording period shown with time of day. Cross marks time that animal left study beach to begin foraging trip. Diamonds indicate still images, circles indicate movies.

A malfunction of the battery in the TDR within the first two hours of the fifth deployment disabled the system preventing image collection because no depth output was available to trigger the camera system. However, this problem was solved by passing a new connection from the TDR to the rechargeable battery for the camera and running both systems from the battery for the camera system.

Images were collected using three recording modes (Table 2): low quality (high compression) still images at 3-sec intervals (mean = 2,753 images, SD 540, n = 2), high quality (low compression) still images at 3-sec intervals (mean = 927 images, SD 12, n = 3), and high quality (low compression) movie images at five frames per second (18 movies, total 24 min 44 sec of footage). The duration of recording varied depending on the recording mode and the seal behavior since some seals had long periods of time between bouts of dives. On average the camera took images over a 0.5-d period (min 0.3, max 1.2 d) of the 4.7–8.3-d foraging trip (Table 2, Fig. 4). The time between leaving the shore and beginning to sample varied between 2.2 and 10.6 h.

The trip durations of animals carrying the UTPR tended to be slightly longer (mean 6.0 d, n = 7) than those recorded over the same time period from 22 other seals which had only radio-transmitters attached (mean 4.5 d, n = 201; British Antarctic Survey, unpublished data).

Still Images

A total of 8,288 still images was recorded over five deployments (Table 3). An average of 8.5% of still pictures (2.4%–11.6%) showed krill (*Euphausia superba*) distinctly (*e.g.,* Fig 5), while at least half the images in each deployment were empty. The presence of downwelling light did not appear to affect whether krill would be recorded. Pictures taken in dark conditions (at night or oriented downwards) contained similar proportions of distinct krill to those taken with surface light present (*e.g.,* w2955: light conditions average 11.1% (n = 2,752), dark conditions average 8.6% distinct krill (n = 541)).

Although sample sizes were small, the two deployments using lower-quality images (high compression) showed similar proportions of identifiable krill (2.4% and 9.0%) to those recorded at higher quality (11.6%, 8.9%, and

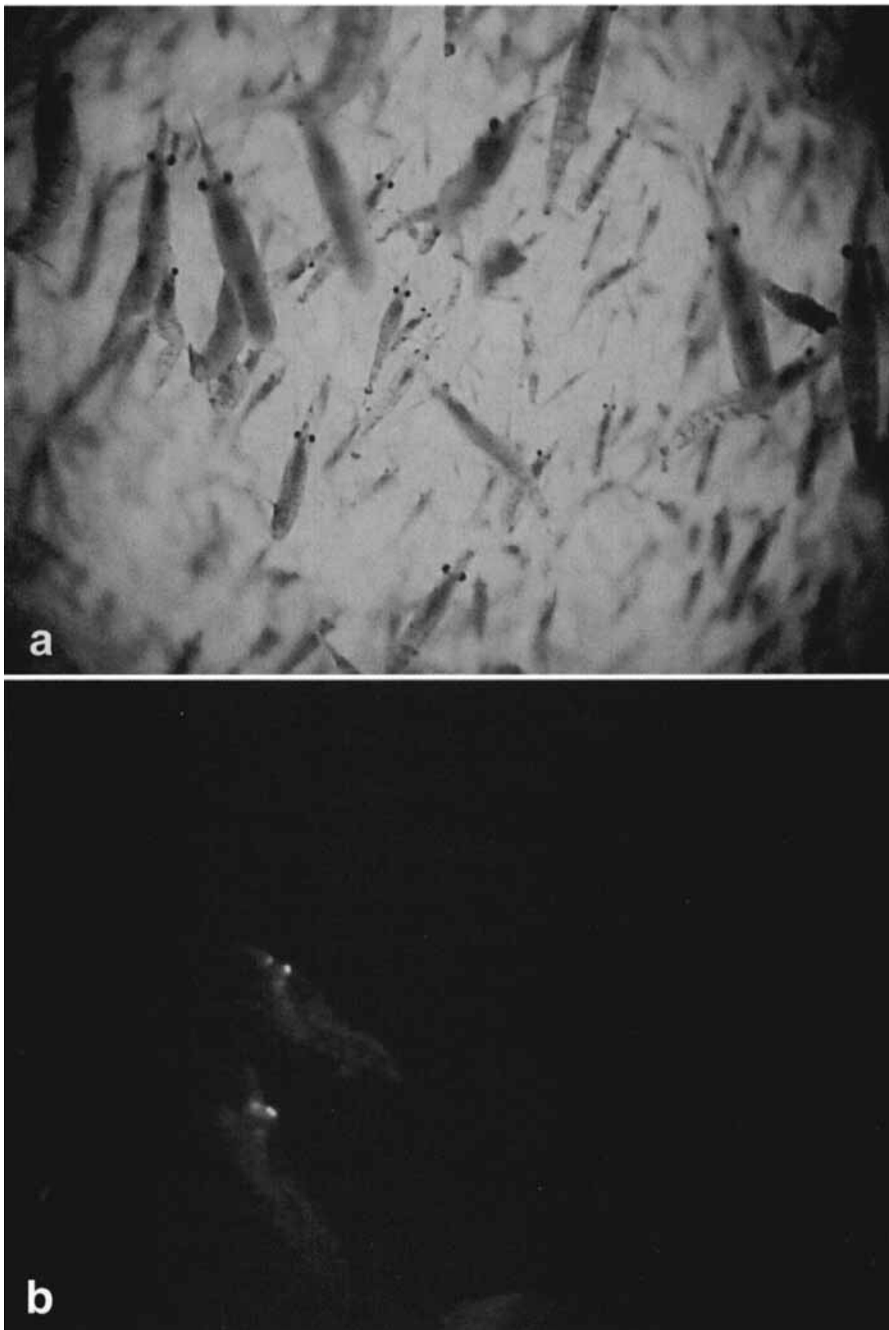

Figure 5. Example digital pictures of krill prey recovered from Antarctic fur seal deployments (a) krill swarm with strong downwelling light, (b) krill taken during night with illumination from the camera.

Figure 6. Example digital picture of another Antarctic fur seal (estimated distance 10 m) foraging in conjunction with instrumented animal. Photo also contains single krill in foreground.

10.7%). However, when images were ranked according to quality, the low compression recordings produced proportionally more high quality images (3.8%, 4.2%, and 4.5% compared to 0.2% and 1.5% from high compression recordings). In one deployment, krill were encountered within 2.5 h (16 km, assuming 1.8 m/sec travel speed, the mean found by Boyd 1996) of leaving the beach. The majority of images of krill were observed between 10 and 50 m depth, although some krill were apparent in images taken at 120 m depth.

Images from five of the six deployments also showed other fur seals foraging near the focal animal (*e.g.*, Fig. 6). Several images also showed bubbles. A general temporal match between observation of other seals in the images from the camera and observation of bubbles suggests that these may have been caused by other seals rather than the study animal.

Movie Images

A single deployment was set to take movie images, resulting in 18 movies (each one representing a single dive) and resulting in a total of 7,598 frames (26 min 38 sec of footage). The first two movies were very short (10 and 21 sec, respectively) and contained no recognizable prey. The other 16 movies, all recorded within a two-hour period, often showed krill swarms and other

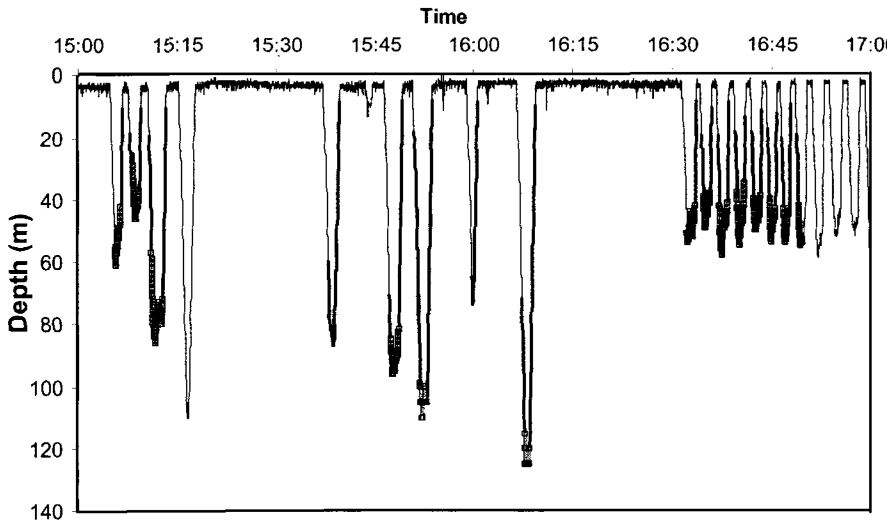

Figure 7. Dive profile of seal (w6714) shown in gray line, with periods during which movies were recorded shown in bold, and times during which krill swarms were visible on these movies shown by squares. Depths at which recording began vary between 15 m or 50–70 m depending on whether the camera was in "standby" or "off" modes (see Fig. 2), and took 5 sec or 43 sec between triggering and beginning recording. Additional minor variations caused by differences in descent rate.

seals. One dive during this period did not trigger the camera. The triggering command from the TDR at the onset of this dive came exactly two minutes after the preceding command to stop recording. It appears that the camera system check, which takes only tens of milliseconds and is run prior to switching off, coincided with the triggering command and resulted in the camera not activating. The likelihood of this occurring was very low and it does not appear to have occurred during any of the 446 dives in the other deployments.

Investigation of the depths at which krill swarms were encountered during dives suggested that the seal followed one krill swarm as it descended out of reach (from 35 to 130 m depth) before beginning a second series of dives on a shallower swarm (45–55 m depth; Fig. 7).

Discussion

This camera system improves upon previous underwater imaging systems because of its smaller size and ease of use. The resolution in the images appeared to be adequate to illustrate the immediate environment in front of a foraging animal (Fig. 5). Although the first trials of this system may have benefited from the swarming and often quite shallow nature of krill, the ability for researchers to modify the sampling procedure over a variety of settings should also suit the wide variety of scenarios likely for other marine mammal species. Furthermore, since the ability to detect prey was not limited to light conditions, this system should work equally well for animals foraging at greater depths. Thus, we anticipate that such a system is likely to supplement standard studies of diving behavior, allowing researchers to monitor the occurrence and identity of prey encountered during dives. Previous studies have illustrated several of the types of results that can be obtained. For example, predator-borne camera systems have allowed investigation of the mechanism of foraging behavior (Davis *et al.* 1999, Ponganis *et al.* 2000), analysis of foraging habitat (Parrish *et al.* 2000, Heithaus *et al.* 2001), and deploying the camera facing backwards (to monitor tail-beat frequency) has allowed investigation of the mechanics of swimming (Williams *et al.* 2000). For research on fur seals the primary benefit is likely to be the ability to link diving behavior with foraging observations and, thus, to investigate prey encounter rate and to examine how decisions regarding dives or bout-ending relate to prey density and depth.

One problem with this first model of UTPR is the differential focus which resulted in poor image quality at the edges of the picture (Fig. 5). New lens types are expected to improve this problem in the next generation of these cameras. The data limitations of this system are similar to those of previous camera models allowing recording over periods of hours to days. For deployments on fur seals, this meant that sampling was restricted to only a few days of the foraging trip. However, this restriction is likely to be somewhat improved in the near future. The data storage capacity of SmartMedia disks together with improvements in battery power will increase the potential deployment duration within the next year or two. For the preliminary test deployments reported here we began sampling immediately, but use of the TDR duty cycling facility in future will enable recording at later stages of the foraging trip.

As with all instruments designed to record behavior remotely, one of the primary concerns is that the recording system might affect the behavior being studied (*e.g.*, Walker and Boveng 1995). Antarctic fur seals are relatively small, but appear to be fairly resilient to the additional energy costs imposed by tag attachment. The size and weight of the instrument used here (10.5 × 8.5 × 5.5 cm; 700 g) is similar in size to the 4.7 × 4.5 × 10.7-cm blocks used to simulate increased foraging costs by Boyd *et al.* (1997). These additional foraging costs were found to cause reduced swimming speeds and behavioral adjustments at the scale of dives, but no difference in prey encounter rate, as shown by the rate of energy delivery to the pup, was observed (Boyd *et al.* 1997). Similarly, in the present study, although trips were slightly longer in duration, the study animals appeared to have little difficulty in locating and targeting krill swarms.

An additional factor to consider in terms of behavioral effect of the instrument is that of the illuminator, since pinnipeds appear to be dark-adapted and may rely on vision even at low-light levels for foraging (Levenson and Schusterman 1999). The near-infrared frequency of light (725 nm) was chosen because pinniped visual acuity is primarily restricted to the blue-green range (<500 nm; Lavigne and Ronald 1975, Peichl *et al.* 2001). Therefore, the near infra-red should have a reduced effect compared to lower wavelengths. Again, the illumination does not appear to have affected the ability of the study animal to locate prey swarms, but further work will be required to investigate this in greater detail. Similarly the illuminator may affect the behavior of prey. Krill show an avoidance reaction to increasing light intensity over periods of seconds (Strand and Hamner 1990). However, the extremely short-burst nature of the illuminator (1/125-sec pulse), particularly for still image recording (a single pulse every three seconds), is unlikely to affect their behavior to the same degree. Over the duration of dives, there was no noticeable decrease in images showing krill, such as might be expected if krill swarms were moving away from the light source of the camera.

Results of these first deployments on Antarctic fur seals concur with previous studies in suggesting the predominance of krill in the diet of fur seals during the breeding season (Reid and Arnould 1996). The preliminary results obtained highlight the potential of this system. The images recorded will allow us to investigate not only the behavior of fur seals but also that of their prey in greater detail. Density estimates of krill swarms are primarily derived from acoustic estimation using echosounders (*e.g.*, Brierley *et al.* 1997), which may suffer from assumptions about the species being detected. Observations carried out by scuba divers (Hamner and Hamner 2000) suffer from being limited to surface waters and the opportunistic nature of such observations. In contrast, the images recorded from foraging fur seals could provide another method by which to investigate both krill swarm densities and the behaviors of individuals (*e.g.*, orientation and cohesion) within swarms in response to predators. In addition, the ability of fur seals to target krill at depths up to 200 m may allow us to investigate the depth-specificity of krill swarms and the response of this to time of day.

In terms of seal behavior, such camera footage can provide unique insights into the functionality of dive types and the detail of fine-scale foraging behavior. Our preliminary results demonstrate that the cohesion observed among fur seals at the surface while at sea is also reflected at depth, with several seals foraging on the same swarm. The numbers of krill observed will allow us to calculate the exposure rate of predators to krill, and to investigate the links between dive types and prey acquisition. At a finer scale, we can begin to investigate the mechanism by which Antarctic fur seals forage on krill, whether there are patterns within dives in terms of separating krill from the swarm, or targetting prey from above or below.

The UTPR is essentially an extension of the TDR system, and as such, deployments are logistically easier on pinnipeds (which can be captured and to which the unit can be glued). However, there is no reason that the UTPR could not be modified with flotation to enable short-term deployment and recovery from cetaceans (*cf.* Baird 1998, Hooker and Baird 2001). Thus, we feel that this system could be applied to a wide variety of marine mammal species, and is likely to dramatically improve our current ability to interpret subsurface behavior.

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